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Orientation of Research Needs Associated with Environment of Closed Spaces*

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New York University

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Introduction

We are well aware of the fact that placing man in a total vacuum, in a hermetically sealed container to live on a normal living process and perform normal work was until recently considered a scientist's dream. It was a matter of small consideration to talk about living conditions of such a man.

As recently as 1950 the writer and others of the New York University Research Division staff began to pose questions about the environment in closed space and discovered that the questions tended to multiply as they opened up additional items that must be fitted into the complex.

A paper presented before the American Astronautical Society in 1957¹ discussed a number of questions and pointed up the need for a study of closed ecological systems and the engineering techniques requisite to handling, treatment, and disposal or recycling of materials appearing as wastes and by-products of human occupancy of the closed space. This study has been undertaken at New York University by the author and his colleagues, Dr. William E. Dobbins, Gail P. Edwards, Mr. Elmer R. Kaiser, Dean Harry J. Masson, Dr. Bernard Newman, Mr. Gerald Levsky, and Mr. Lawrence Slote. The discussion that follows represents the consensus of thinking on the part of the entire staff after review of literature, conferences and field visits to other locations where research on the closed space ecology and its problems has been in progress.

In the course of the literature search some 160 articles have been sufficiently informative to justify preparation of briefs on content. These are part of the overall report to the Air Force Office of Scientific Research.² From the information thus obtained an assessment and review of present knowledge has been developed on such essentials as CO₂-O₂ conversion; treatment of bodily wastes; recovery of usable water from contained urine, and other sources; removal of pollutants from contained air; and purification or disposal of liquid wastes.

The conditions applicable to the need for any or several of these essentials are related to the duration of extra-terrestrial flight. Such flight may be (1) of short duration, amounting to hours; (2) of intermediate duration, amounting to days; and (3) of long term,

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amounting to weeks and months. This discussion deals almost entirely with the third problem, but the orientation of research needs emphasizes that careful study should be made of factors affecting weight and volume of equipment required to process and maintain an environment with total conservation of mass balance and recycle of matter, as opposed to the principle of replacement of essentials such as oxygen and water by withdrawal from storage while polluted matter is ejected from the closed system environment.

For conditions introduced by flight of short or intermediate duration, engineering economics may justify provision for partial or even total replacement of environmental constituents. Long term operations seem impractical without plans for cyclic-use of the contained matter. Commentary and discussion of research needs related to the environmental complex will demonstrate the possible areas of research which may lead progressively to a healthful working space under a closed ecology.

Bodily Wastes

The handling of feces and urine, normally a matter causing little concern, can become a serious problem in a closed ecology. Gradwohl³ has listed the more important products present in feces:

Indole	C ₈ H ₇ N		Odorous
Skatole	C ₉ H ₉ N		Odorous
Paracresol	C ₇ H ₈ O		
Para-oxyphenyl-propionic			Acid
Volatile fatty acid			
Hydrogen sulphide		H ₂ S	Odorous
Methane	CH ₄		
Methylmercaptan			Odorous
Hydrogen	H ₂		
Carbon dioxide		CO ₂	
Proteoses			
Peptones			
Peptides			
Ammonia		CH ₃	Odorous
Amino acids			
Some raw vegetables, unchanged, such as radishes, cole slaw, pickles, onion, skin of fruit, nuts, berries			
Mucus			
Tissue remnants, epithelial cells, muscle fibers, connective tissue			
Crystals, phosphates and many others			
Detritus			
Fats, neutral, free fatty acids or soaps, approx. 2 gm. daily			
Starch granules			
Bacteria, a great variety.			

Urine Constituent

Water	1200
Solids	60
Urea	30
Hippuric Acid	0.7
Uric Acid	0.7
Creatinine	1.2
Indican (Indoxyl Potassium Sulfate)	0.01
Oxalic Acid	0.02
Allantoin	0.04
Amino Acid Nitrogen	0.2
Purine Basis	0.01
Phenols	0.2
Cl as NaCl	12.0
Na	4.0
K	2.0
Ca	0.2
Mg	0.15
S as SO ₂	2.5
Inorganic Sulfates as SO ₃	2.0
Neutral Sulfur SO ₃	0.3
Conjugated Sulfates as SO ₃	0.2

Bodansky and Bodansky, as reported by Bockus,⁴ in a study of feces of 40 males and 40 females found the mean total fat to be 17.5% of the dry material. About $\frac{1}{3}$ of the total fat was free fatty acid and 42.0% was neutral fat. The water content of feces has wide range but a mean of 78.9% was reported in the above study as the difference from a mean 21.1% dry solids. Information from a number of sources is such that for estimating purposes it would be safe to assume a 75% moisture content and a 25% dry solids basis.

The quantity of feces per person is, of course, related to diet, and from both literature and studies by this author⁵ it appears that a range of 100 to 150 grams per day per person is to be expected. Gradwohl³ suggests an average of 102.8 grams per person per day. It may be estimated that dehydrated fecal material would amount to 20–25 grams per person per day. This quantity is small, but the difficulties in handling are many. At reduced atmospheric pressure outgassing may be anticipated. Hence, there is the need for rapid transfer to a closed system of handling so that the gases do not enter the atmosphere of the occupied closed space. Much of the water in feces is bound water and its recovery by extraction needs to be considered only for emergency. The basic problem appears to be one of handling and storage.

Heat followed by freezing or even freezing alone will suffice to inactivate the material and permit its storage at 0°F. or lower. It is believed that the cubage required for storage of even as much as 0.5 lbs. per day would not be above 0.02 cubic feet per day, and might be considerably less. It is a matter of conjecture at the moment as to the cubage that might be required for equipment to inactivate and freeze material for storage. Research on this matter should be directed toward determination of methods suitable for sealing off the material after evacuation and preparing it for storage.

Flatulence will, of course, contribute unwanted gases to the closed space. Work of Fries is reported by Alvarez⁶ to indicate that about one liter of gas per day is passed. The composition will vary with diet. Alvarez,⁶ reporting on work of Ruge, has published the following information on the probable volumetric composition:

Gas	Milk Diet		Meat Diet			Diet of Legumes		
			24 hrs.	48 hrs.	72 hrs.			
%	%	%	%	%	%	%	%	%
CO ₂	16.8	9.0	13.6	12.5	8.5	34.0	38.4	21.0
CH ₄	0.9	0.0	37.4	27.6	26.5	44.6	49.4	55.9
H ₂	43.9	54.8	3.0	2.1	0.7	2.3	1.6	4.0
N ₂	38.4	36.7	46.0	57.9	64.4	19.1	10.7	18.9

Flatulence will mingle with the room air and must be considered among the items to be treated in connection with purification of the closed space atmosphere.

Urine also is variable in quantity and composition. Hawk and Bergeim⁷ report the following:

Urine is a possible source of usable water and may be a source of nutrients to be used in connection with algae culture. However, it contains substances that may be toxic and therefore its possible treatment to recover usable water requires careful and extensive exploration. Dr. Newman of the project staff has done some exploratory work on this question. We find that distillation of a sample delivers unsuitable water at the beginning and end of the action. Approximately one-half of the sample delivered is of such quality that it might be subjected to further treatment in ion exchange beds and with activated carbon and possibly additional filtration. However, the present thinking is that freezing techniques may offer a better quality of recovered water. It seems essential that research on the recovery of usable water from urine be explored fully.

Excretions from sebaceous glands and sweat glands contribute impurities to the contained air in the form of water, salts, and detritus. Howell,⁸ reporting on quantity of water loss, indicates that 25 to 40 grams per hour are lost through insensible perspiration with $\frac{1}{3}$ to $\frac{1}{2}$ of that being given off from lungs. Approximately 600 ml. of water is released from skin per 24 hours. However, the quantity may reach 2500 ml. per hour with strenuous muscular work. CO₂ release is estimated at 7–8 grams per 24 hours and increasing with sweating.

Ingram,⁹ in a progress report on the project, discusses skin excretions. The skin surface usually has an acid reaction and may exert a bactericidal effect. Lipids and fat may interfere with this reaction. The water vapor loss from epithelial evaporation (insensible perspiration) does not carry over solutes. However, sweat glands do release many electrolytes, organic acids, and compounds, and inorganic salts in minute quantities. Sebaceous gland secretions are mixed with sweat and the composition is not exactly known. The fatty oily material does contain in small quantities, cho-

l, some simpler fatty acids, fatty acid esters, albus, and inorganic salts. The sebum may spread over skin in a protective layer or may pack in the gland-aneous surface as a cheese-like mass. Organic con-
nents of what is thought to be a mixture of seba-
us and sweat gland excretion is believed to include
all quantities of urea, uric acid, creatinine, lactic
l, ethereal sulphates of phenol and skatol, amino
ls, sugar in traces, and albumin.

review of the chemical composition of sweat by
inson and Robinson²⁰ offers a range of values rec-
ed by various research studies. The components
here summarized:

Sodium Chloride

NaCl and water are the principal substances
whose loss by sweating may affect the homeostasis
of the individual to a serious degree. Concentration
of NaCl is variable. Individual values as low as
as 5 mEq/l to as high as 100 or 148 mEq/l have
been reported. Average values ranging from 18-
97 mEq/l have been reported in at least 86 sepa-
rate studies. Normal output from skin (no sweat-
ing) is ca. 0.2 mEq/hr. of Cl⁻. Sodium runs some-
what higher because of other sources of Na.

Potassium

Lower than Na averages about 4.5 mEq/l with
range from 1 to 15 mEq/l. Potassium concentra-
tion varies inversely with the Na concentration
and the Na/K ratio varies directly with the Na
concentration. Na/K = 15 in unacclimatized men,
dropping to 5 after a five-day adaptation period.

Calcium

Ranges from 1 to 8 mgm per 100 ml.

Magnesium

0.04 to 0.4 mgm/100 ml.

Copper

4.4 to 7.5 mcg/100 ml.

Manganese

3.2 to 7.4 mcg/100 ml.

Sulphates

4 to 17 mgm/100 ml.

Iron

0.1 to 0.2 mgm/100 ml.

I₂, F₂, Br₂ have been reported.

Lactic Acid

Values reported range from 4 to 40 mEq/l.

pH

Most observers found between 4 and 6.8.

Glucose

Extremely low. Reported from 0.1 mgm/100 ml.
to 9 mgm/100 ml.

Nitrogen

Much more dilute than corresponding values in
urine. Average values range from 23 mgm/100 ml.
(tot. N) to 140 mgm/100 ml.

Urea N.

Averages ranged from 12 to 39 mgm/100 ml. in
several studies.

15. *NH₃N*

Most investigators report in range of 5 to 9 mgm
per cent

16. *Creatinine*

Ranges from 0.1 to 1.3 and averages 0.4 mgm/
100 ml.

17. *Uric Acid*

Reports range from 0 to 1.5 mgm/100 ml.

18. *Amino N.*

Extremely low, but 18 different amino acids
have been identified.

19. *Phenol and Histamine* reported.

More should be known about the sebum, both quan-
titatively and as to deterioration. Study of determina-
tion of sweat gland excretions is also indicated. The
wastes resulting from personal ablutions containing
skin excretions should be investigated to determine
means of safe disposal or recovery for reuse.

Wastes Handling and Treatment

The wastes of a closed ecology occur as liquids, solids,
and gases. Gaseous components are associated with
both liquid and solid phase waste and are a principal
consideration in the closed space air. Solids in quantity
result from feces, but are also to be considered as a
small but important constituent of urine, personal and
other cleansing operations and room air.

Algae Culture

Attention has been given the idea that liquid wastes
might contribute a source of nutrient in algae culture.
If so, the dual problems of waste treatment and CO₂-
O₂ balance might have common solution. The green
algae, chlorella and scenedesmus, have been used in
studies of photosynthesis. Chlorella has a high rate of
photosynthesis and low (by comparison) rate of respira-
tion. Hence it has offered seeming advantages in the
establishment of CO₂-O₂ balance. Edwards¹¹ has ex-
plored the literature extensively with respect to algae
culture, and has enumerated as a part of that study
what appeared to be desirable characteristics which
an alga suitable for use in a confined space should have.
The species of algae developed should:

1. Grow efficiently at a high temperature, say
40-50°C.
2. Give a high growth rate with higher rates of evolu-
tion of oxygen.
3. Derive part of its CO₂ needs from bicarbonate ion
(danger of high pH resulting would need phosphate
buffer—perhaps).
4. Grow in mass culture without change over long
periods by recirculation of media.
5. Be very hardy—resist contaminating agents and
inhibiting substances.
6. Have a pleasant flavor.
7. Be free from toxic substances.
8. Produce no substances which would inhibit its own
growth.

9. Have good food value—as complete as possible—easily digestible.

10. Be able to utilize the nitrogen from urine.

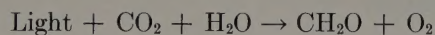
It does not appear at the moment that algae can be utilized as a means of waste treatment, since the waste would have to be treated extensively before admission to the culture. There are many problems requiring further study before algae culture can be accepted as a means of obtaining $\text{CO}_2\text{-O}_2$ balance under closed space conditions.

In addition to the development of more suitable strains of organism, consideration should be given to possible mutation effects, the establishment of suitable and easily supplied sources of nutrient, possibly from chemicals, urine and wastes, toxicity of the developed algae if used as part of human diet, the control of growth of biological contaminating agents, and the development of processing and harvesting equipment that will meet both cubage and weight requirements.

$\text{CO}_2\text{-O}_2$ Conversion

Since there are some possible limitations of growth of algae for maintaining $\text{CO}_2\text{-O}_2$ balance, it has been necessary to examine other possible methods of attaining CO_2 conversion.

The treatment which has been occurring in nature is the process of photosynthesis. In simplified form the reaction may be written:

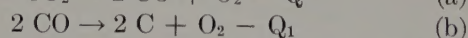
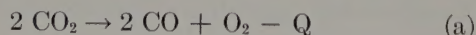


Another possible form of the reaction might be:



If this reaction can be made to take place in a non-living system (artificial photosynthesis), one might anticipate that oxygen would be made available and that a carbohydrate would be formed that might be made available for food or fuel or auxiliary energy. CO_2 would be removed as part of the reaction. Matters of materials balance and energy balance are involved here. A catalyst of some type is required. In nature the catalyst is chlorophyll.

When carbon dioxide is heated to higher temperatures it breaks down in one of two reactions, or possibly both:



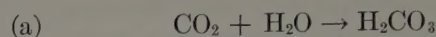
The temperatures required for the reactions are high. Masson has this to say in his report.¹²

(1) reaction (b) in all probability does not take place at least under conditions ordinarily attainable and (2) that even for this reaction (a) the temperatures required are very high (3000°C —app. 5400°F). At these temperatures the amount of molecular is only 18%. Higher temperatures serve only to dissociate the molecular oxygen into atomic oxygen. If the oxygen is to be recovered from the equilibrium

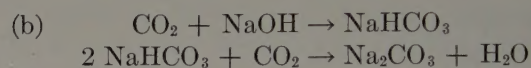
mixture it would have to be cooled very quickly to prevent the reverse reaction taking place. It would be unusual if the recovery was more than 10%. The production of such high temperatures is a difficult one attainable probably only by means of an electric arc or sparks or solar furnace.

The carbon monoxide produced is very poisonous but could be converted to a harmless and perhaps ecologically useful product.

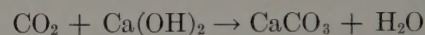
In the foregoing reaction the form of energy to bring about the dissociation is thermal. It might be fruitful to combine this with other forms of energy. Masson also explores the reaction of CO_2 with other substances. The following are actual or potential reactions:



This is the normal reaction with water at room temperatures, but the product is unstable and is easily decomposed by a modest rise in temperature. This reaction should not be confused with that of photosynthesis.

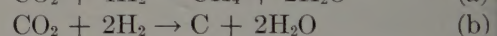
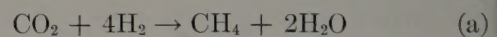


These reactions may be used to remove the CO_2 from the enclosure but the use of $\text{Ca}(\text{OH})_2$ is superior.

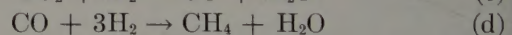
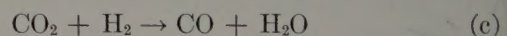


The CaCO_3 is insoluble.

(c) The reactions between carbon dioxide and hydrogen are interesting. They are:

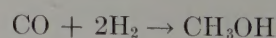


related reactions are:



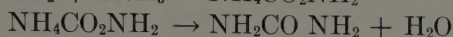
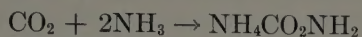
The foregoing reactions can be carried out under the environmental conditions existing in the closed system. The H_2 may be obtained by the electrolysis of water.

In addition to the above reactions there is a vast spectrum of reactions by means of which many useful compounds may be produced. For example, the methane can be converted to C_2H_4 and C_2H_2 which in turn can be converted to C_6H_6 and other cyclic compounds. Or the following catalytic reaction may be used to produce methyl alcohol:

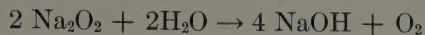


Depending upon the choice of catalyst ethyl alcohol, acids and esters may be produced.

(d) Excreta, etc. can be decomposed to form NH_3 or the ammonia may be formed from other sources. In any case there is a significant reaction between CO_2 and NH_3 .



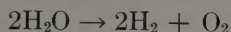
(e) If concern is for the production of O_2 there are the reactions of water with alkali peroxides, i.e.:



1 lb. Na_2O_2 produces 2.3 cu. ft. of O_2

1 lb. Li_2O_2 produces 3.9 cu. ft. of O_2

or by the electrolysis of water:



Explorations and more intensive research into CO_2 - O_2 conversion may be productive in the following channels of effort:

1. Induce greater efficiency in natural photosynthesis by acceleration of growth, using substances such as gibberelic acid.
2. Investigate means for creating a synthetic cell using organic dyes and enzymes as chloroplasts.
3. Study the effect of various forms of energy on the decomposition of carbon dioxide.
4. Study the effect of the bombardment by electrons on carbon dioxide in various physical states.

Closed Space Air

The closed space air must be maintained in such condition that men can live and work in it. Palevsky¹³ discusses the several considerations involved. The control of temperature, humidity, air motion, foreign matter, microorganisms, and the balancing of the CO_2 - O_2 ratio are all major factors to be considered in making the environment acceptable for habitation. The ventilation of the confining space is not merely the supplying of fresh air, or the replacement of spent O_2 , but encompasses the exhausting of heat, dust, toxic gases, fumes and noxious odors which may be present in the sealed space, while returning a usable, uncontaminated air. An examination of each of the above mentioned, singly and in relationship with each other, is necessary for an understanding of the problems of ventilation and air conditioning.

There are three general methods of reducing the moisture content of the air: by compression, by adsorption, and by cooling. Cooling below the dew point and condensing or freezing out the moisture is the most common method of dehumidifying. For this purpose the concepts employed in present day commercial equipment may be utilized to produce the desired effects within the closed ecological system. Modifications with respect to size and weight may have to be investigated.

Another possibility is the utilization of the temperature gradient across the hull of the cabin. Exploratory investigations of the temperatures¹⁴ suggest that at

some location the cabin structure will have temperatures low enough to allow the use of freeze-out techniques. The engineering design of such a system requires more thorough investigation to determine its feasibility.

That dehumidification is necessary for comfort control is elementary, but more important is the fact that condensed water vapor from the enclosed atmosphere is one of the probable sources of water supply within the closed ecological system.

The water vapor that is condensed out of the contained atmosphere probably may be a purer and less contaminated source of water than any bodily waste.

Normally the air surrounding a living and breathing body is carried up by its own warmth and consequent lightness, thus allowing fresh air to take its place. But in a gravitationless system neither fresh nor foul air has weight, and there can be no convection currents. Without air circulation, heat discharged from the body would hang against the body causing intense perspiration, which in a saturated atmosphere would not evaporate. Body cooling effect would therefore be minimal. Non-circulation effects would also hold for the expired air. In a non-circulating atmosphere a motionless human body would soon become enveloped in expired air, rich in CO_2 and water vapor.

Air motion imparted mechanically by a fan or other stirring mechanism to maintain the entire enclosed atmosphere in a state of turbulence or agitation is necessary.

In any confined area in which activities transpire there are always to be found impurities or foreign matter in the air. These materials are usually particles of organic matter which come from nose, mouth, and skin, and particles derived from the attrition of surfaces. These particles tend to produce odors. The organic particles produce normal body odors which are usually perceived in unventilated or even poorly ventilated areas. Within the contained atmosphere these body odors are to be anticipated and others which are not normally considered must be added.

It has been stated that odors of themselves are not injurious to health, but indirectly they may affect health. As odors become extremely noxious, shallow breathing may induce O_2 deficiency and its sequelae.

At this time too little is known about the breakdown products and subsequent gasification of body oils, gland secretions, flatulence, halitosis, and bodily waste products to be certain of their non-toxic effects when accumulated in an atmosphere after cycles of reuse.

The air purification system is envisioned as a train of absorbents and adsorbents which will remove the contaminants from the air by physical processes, chemical reaction or electrostatic attraction. Solid state rather than liquid phase materials should be employed in order to prevent as much as possible additional pollutant carry-over in the air stream and subsequent condensation in the water supply.

H. L. Barneby,¹⁵ in a paper discussing the activity of activated charcoal required for air purification, offers a table which gives some rough idea of the quantity of charcoal required per year for odor concentrations of difficult intensity. As a guess, an odor index of 2, 3, or 4 might be anticipated in the closed space. This corresponds to 0.1, 1.0, and 10 pounds of odor per million cubic feet. One pound per year of charcoal is required to treat 100, 10 or 1 cubic feet of space at the respective levels of concentration. Accordingly, for a space of 1,000 cubic feet the amount of charcoal required may be between 10 and 1,000 pounds. It should be noted here that this amount is only enough to provide for odor removal and is predicated on the assumption that some fresh air is available due to building leakage. It is also important that activated charcoal is not provided for CO₂ adsorption. Barneby points out that activated charcoal is relatively inefficient in removing CO₂ and should not be depended on for that action.

Experiments conducted in 1942¹⁶ have shown that recycling of air in a closed room through air filters does little to change the overall room microorganism concentration, even though a large number of organisms are caught on the filter. Newer types of air filters of the millipore type, or the impregnated resin deep filters are capable of removing over 99% of the organisms from air drawn through the filter,^{17, 18} but the residual concentration of microorganisms in the enclosed atmosphere may still be high.

Germicides, glycol sprays and other similar airborne materials may have a beneficial effect in reducing bacterial numbers, but their effect on humans under confined conditions with continuous inhalation and ingestion would require thorough study before they could be considered safe for use.

In summary it appears that temperature control, air motion development, removal of particulate matter, elimination of odors and control of microorganism populations seem feasible with modifications of present day commercial equipment. A train of materials can

be established such that turbulent air from the confined cabin would be drawn through an activated carbon filter, a millipore, or deep bed filter, and chemical train for specific materials such as CH₄, H₂S, and any others that may become apparent as more analyses of breakdown products are conducted.

By the time the air has passed through the train most of the gross impurities have been removed. This leads to the assumption that the room air may provide the purest source of water available in the confined ecological system. This supply of water developed from the water vapor would undoubtedly contain small amounts of entrained or dissolved gases. What the effect of these small amounts might be on the human system is not known, nor did any of the library references examined indicate study in this field.

It is conceivable that the human body, which is a well-organized purification unit, can receive these materials through inhalation, skin, or oral intake, and detoxify them, if necessary, passing them out as waste products. If this be the case, many problems of train contaminant removal are simplified by having the human body act as its own purification plant.

Further research is much needed in conjunction with the problem of air conditioning for a closed ecological system to ascertain the toxic limits for humans of the several material exposures by ingestion, by inhalation, and by skin absorption.

From the foregoing discussion it is obvious that there are many environmental factors that require research. Not until closed space air is maintained at safe and healthful levels, polluted liquids and objectionable solids are treated or safe practice in handling and disposal is devised, will it be possible to maintain human life for weeks or months in a closed space. The processes that are employed must not fail, since the environment will be totally dependent on the continuous and proper functioning of reclamation and conversion operations.

It is to be anticipated that research directed along paths suggested here will permit early development of methods, processes, and equipment required.

References

1. INGRAM, WILLIAM T., "Environmental Problems Connected With Space Ship Occupancy," Preprint No. 56-20, *Proceedings of the American Astronautical Society*, 3rd Annual Meeting, N. Y. (Dec. 7, 1956).
2. INGRAM, WILLIAM T., AND COLLEAGUES, "Report on the Engineering Biotechnology of Handling Wastes Resulting from a Closed Ecological System," New York University, College of Engineering, Research Division, N. Y. (Feb., 1958).
3. GRADWOHL, R. B. H., "Clinical Laboratory Methods and Diagnosis," Chapter VIII, Vol. 2, C. V. Mosby Co., St. Louis, Mo. (1956).
4. BOCKUS, HENRY L., "Gastro-Enterology," Vol. 2, W. B. Saunders Co., Philadelphia, Pa. (1944).
5. INGRAM, WILLIAM T., "An Investigation of the Treatment of Cabin Cruiser Wastes," *Sewage and Industrial Wastes*, **28**, 1, 93 (Jan., 1956).
6. ALVAREZ, WALTER C., "An Introduction to Gastro-Enterology," 3rd Edition, P. B. Hoeber, N. Y. (1939).
7. HAWK, PHILIP B. AND BERGEIM, OLAF, "Practical Physiological Chemistry," 11th Edition, P. Blakiston's Son and Co., Inc., Philadelphia, Pa. (1937).
8. HOWELL, WILLIAM H., "A Textbook of Physiology," 14th Edition, W. B. Saunders Co., Philadelphia, Pa. (1940).
9. INGRAM, WILLIAM T., Progress Report, "Skin Excretions," Part of Report on the Engineering Biotechnology of Handling Wastes from a Closed Ecological System, New York University, College of Engineering, Research Division, N. Y. (Feb., 1958).

0. ROBINSON, S. AND ROBINSON, A. H., "Chemical Composition of Sweat," *Physiological Reviews*, **34**, 202 (Apr., 1954).
1. EDWARDS, GAIL P., Progress Report, "The Culture of Algae," Part of Report on the Engineering Biotechnology of Handling Wastes from a Closed Ecological System, New York University, College of Engineering, Research Division, N. Y. (Feb., 1958).
2. MASSON, HENRY J., Progress Report, "Study of Methods for Obtaining Oxygen from Carbon Dioxide," Part of Report on the Engineering Biotechnology of Handling Wastes from a Closed Ecological System, New York University, College of Engineering, Research Division, N. Y. (Feb., 1958).
3. PALEVSKY, GERALD, Progress Report, "Handling Air Contaminants Resulting from a Closed Ecological System," Part of Report on the Engineering Biotechnology of Handling Wastes from a Closed Ecological System, New York University, College of Engineering, Research Division, N. Y. (Feb., 1958).
14. SLOTE, LAWRENCE, Progress Report, "Thermal Energy Exchange With Specific Application to Waste Handling in a Closed Ecological System," Part of Report on the Engineering Biotechnology of Handling Wastes from a Closed Ecological System, New York University, College of Engineering, Research Division, N. Y. (Feb., 1958).
15. BARNEBY, H. L., "Quantity of Activated Charcoal Required for Air Purification," unpublished paper, Barneby-Cheney Co., Columbus, O. (May, 1957).
16. YAGLOU, C. P. AND WILSON, U., "Disinfection of Air by Air Conditioning Processes," *Aerobiology* (Publication of the American Association for the Advancement of Science), No. 17, 1942.
17. ———, "Filtration of Very Fine Dusts," *Engineering*, **179**, 607 (May 13, 1955).
18. HUMPHREY, A. E. AND GADEN, JR., E. L., "Air Sterilization by Fibrous Media," *Industrial and Engineering Chemistry*, **47**, 5, 924 (May, 1955).

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Prediction of Cratering Caused by Meteoroid Impacts^{*}

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Abstract

Data from high-speed laboratory experiments, explosive craters, and meteorite impacts are correlated to obtain an approximate expression for depth of penetration in terms of target material properties and kinetic energy of the impacting particle.

Nomenclature

- c Speed of sound in target material
- D Diameter of crater (see Fig. 1)
- E Young's modulus of target material
- E_0 Reference Young's modulus = 10^6 psi
- h Depth of crater (see Fig. 1)
- M Mach number relative to target material, v/c
- U Kinetic energy of projectile before impact
- v Speed of projectile before impact
- V Volume of crater (see Fig. 1)

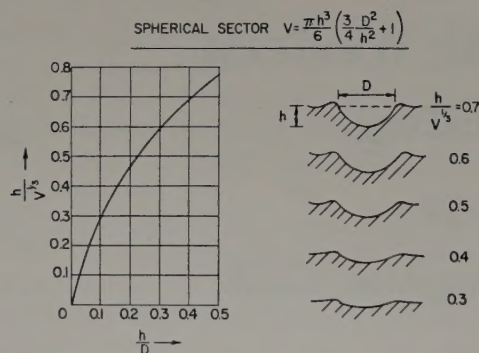


FIG. 1. Ideal Crater Shapes

Introduction

The practical problem of prediction of meteoroid cratering may logically be separated into two distinct problem areas:

- a) The probabilities of collisions with meteoroids of all sizes and velocities.
- b) The estimation of the crater size resulting from each collision.

Assuming that the two solutions are completely independent of each other when applied to any practical situation, (and since the two problems call for the use of widely different scientific disciplines,) only the latter

task is undertaken in this paper. The objective of the analysis, therefore, is to predict the depth of the crater formed when a particle of known mass and velocity impacts upon a surface with known physical properties.

The formation of a crater on the surface of a semi-infinite plane target, whether caused by the penetration of projectiles at high speeds or by explosive attack, is a phenomenon which is the subject of considerable theoretical and experimental investigation currently. The impetus for these investigations has been provided by the need for military information on the cratering effects of large weapons and, in the case of high-speed impact, by the need for estimates of the effects of meteoroid impact on satellite vehicles, ballistic missiles, and space ships. This paper is concerned primarily with the latter problem of hypervelocity impact, although it is found that experimental data obtained with explosives can be correlated with the impact data and are useful in filling certain gaps in the cratering picture.

Although much effort has been expended in development of a theoretical treatment of the mechanics of the high-speed cratering process, reliance will not be placed upon such theories for quantitative estimates. Instead, theoretical predictions will be used only as a basis for selecting physical parameters of significance in correlating the experimental data and extrapolating to situations not covered by the experiments.

That such extrapolations are necessary, at present, is evident from an examination of Table I, which shows laboratory data one order of magnitude too low on velocity and three orders of magnitude too high on size of impacting particle. Since it is known that the mechanism of cratering is different at low and at high speeds (considering a ductile target material, for example, at low speeds the missile penetrates into the target making a hole with diameter of the same order as the missile size; while at high speeds the missile shatters and produces a bowl shaped crater, as in Fig. 1, many times the diameter of the missile), the question arises whether one can extrapolate from the 5 km/sec data to the 73 km/sec condition. The justification for this extrapolation is based on the combination of the particle impact data obtained in the laboratory with certain aspects of the explosive cratering data and the meteorite crater information.

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TABLE I

Test Data Compared with Environmental Conditions of Meteoroid Impact.

Environmental Condition Laboratory Test Data

Impact Velocity	11-73 Km/sec*	<5 Km/sec
Minimum size of projectile	~2 microns†	~ $\frac{1}{8}$ "
Target Material‡	Any	Aluminum, Brass, Clay, Concrete Magnesium, Copper, Lead, Plaster-of-paris, Rock, Sand, Soil, Steel, Wax Wood, Zinc, etc.

* See Reference (1). Note that 1 Km/sec = 3280 fps

† It has been theorized that light pressure from the sun will blow very tiny particles away from our solar system. Although this lower limit on size of meteoroids is very much in doubt, it is found to be an important element in the calculation of surface roughness caused by meteoroid impacts.

‡ It is estimated that the material properties of the projectile are relatively unimportant

Impact experimentation has been done with pellets of the order of $\frac{1}{8}$ " in diameter or larger, whereas the meteoroid impacts of statistical significance for many applications (particularly when surface roughening is a serious consideration) are estimated to occur with particles below about 100 microns (0.004") in size. It is therefore necessary to use scaling laws and to estimate scaling errors due to "size effects", although it is problematical that such a procedure is valid down to particle sizes of the same order as the grains or crystals of the target material.

The approach which follows is to analyze the volumes of craters and the shapes of craters separately, and then to combine these analyses to arrive at a formula for depth of meteoroid craters. The reasons for this method of approach are the following:

(a) The scaled volumes of craters are found to be relatively independent of size and velocity effects, and may be related directly to the target materials.

TABLE II

Experimental Data—Crater Volumes

Material	Density lb/cu. in	c, fps	E lb/sq in	Avg. V/U cu in/ in lb	$\frac{VE}{U}$	Source of $\frac{V}{U}$ data
Aluminum 24ST	0.098	17,000	10×10^6	2.5×10^{-6} 3.8×10^{-6}	25 38	Fig. 4 Ref. 3
Magnesium	0.063	17,000	6.5×10^6	4.2×10^{-6}	27	Fig. 7
Magnesium-Lithium 6:1 by wt.	0.056	*4,500	* 0.43×10^6 (calculated)	2.8×10^{-6}	*1.2	Fig. 5
Steel	0.28	17,000	30×10^6	0.76×10^{-6} 2.2×10^{-6}	23 66	Ref. 4 Ref. 3
Brass	0.31	12,000	16×10^6	0.62×10^{-6}	10	Fig. 3
Lead	0.41	4,000	2.56×10^6	25×10^{-6} 28×10^{-6} 34×10^{-6}	64 72 87	Fig. 2 Ref. 7 Ref. 7 explos.
Zinc	0.26	7,900	6.0×10^6	1.4×10^{-6}	8.4	Ref. 4
Copper	0.32	11,900	16×10^6	4.6×10^{-6}	74	Ref. 3
Wax (50°F)	0.032	2,100	~50,000 (Calculated)	62×10^{-6}	3.2	Fig. 6
Concrete	0.087	10,000	3×10^6	350×10^{-6} 9.7×10^{-6}	1000 29	Ref. 6 Impact Contact Explos.
Plaster-of-paris	0.081	10,000	3×10^6	38×10^{-6}	114	Ref. 10
Soft Rock	—	—	—	1460×10^{-6}	—	Ref. 7 Impact
Soil	~0.050	~500	2000-5000	1460×10^{-6}	5.1	Ref. 7 Explos.
Sand	~0.058	~500	Ref 4000-10,000	1270×10^{-6}	8.9	Ref. 6
Clay	~0.058	~300	11 2000-4000	2310×10^{-6}	6.9	Ref. 6

* c = 4500 fps appears unreasonably low. Use of c = 14,000 fps results in much better correlation of VE/U —See Figure 8

(b) The shapes of craters, although more heavily dependent on size and velocity effects, may be extrapolated into the high velocity regions characteristic of explosions and meteorite craters (terrestrial and lunar). This type of experimental information may not be used in the volume analysis, since one does not know the size or kinetic energy of the meteorites. However, knowing the order of magnitude of the impact velocities of the meteorites enables one to extrapolate the crater shape data from low Mach numbers (projectiles from guns) to low supersonic Mach numbers (explosions) to hypersonic Mach numbers (meteorites), with earth as the target material.

The Volumes of Craters

One of the earliest correlations of cratering data was made by Felix Helié in the middle of the nineteenth century (Ref. 2), who observed that the volume of the crater was roughly proportional to the kinetic energy of the impacting projectile, the constant of proportionality being a function of the target material. Later investigators, in general, have agreed with Helié's conclusion (Ref. 3, 4) with some exceptions (Ref. 5). In order to evaluate the validity of the constant volume-energy ratio for a given target material, the experimental data will be examined to determine whether this ratio is independent of velocity, material, and size of projectile.

Figures 2 through 7 present the bulk of the laboratory data on cratering at high speeds, taken from Ref. 3, 4, and 5. Examination of Figures 2, 4, and 5 shows no size effect on the volume-energy ratio. Figures 2, 3, 5, 6, and 7 indicate no clear influence of Mach number on the V/U ratio; however, Figure 4 with its rather extensive data on aluminum, does indicate an increase in V/U with M at least in the subsonic range covered by the data.

Some very rough data on the cratering of concrete has been extracted from Ref. 6. For projectiles of weights from 1.70 lbs. to 1000 lbs. striking concrete at about 1000 fps, the volume-energy ratio varied from 230×10^{-6} to 470×10^{-6} cu. in./in. lb. with no discernible dependence on size of projectile. Data is also available for steel, zinc, copper, plaster-of-paris, etc. but these data did not cover a sufficient range of velocities or sizes to make correlations possible.

Hope of discovering crater volume effects at high Mach numbers is afforded by the data on explosive craters in soil. It has been shown (Ref. 7) that the volume-energy ratio for buried explosive charges is of the same order of magnitude as the ratio for impacting projectiles, and the Mach numbers may be higher. If one permits the use of the concept of an effective impact velocity for an explosive charge based on the idea of an expanding sphere of gas of density equal to that of the explosive charge, and impact speed that of the rapidly expanding gas, then one may expect high explosives to produce an "impact speed" of about 5000 fps (rather than the commonly quoted detonation

speed of about 20,000 fps—see Ref. 8) and atomic explosions to have an "impact speed" an order of magnitude or two above that figure. Ref. 7 quotes a volume-energy ratio of about 1460×10^{-6} cu. in./in. lb. for small caliber impact on soft rock at a Mach number of perhaps 0.5, analysis of data in Ref. 6 on explosive craters in soil results in a peak volume-energy ratio (at optimum depth of the charge) of 2310×10^{-6} cu. in./in. lb. for clay and 1270×10^{-6} cu. in./in. lb. for sand at Mach numbers of the order of 10 to 15, and atomic explosion cratering at extremely high Mach numbers shows volume-energy ratios between 600 and 900 cu. in./in. lb. with the ratio decreasing as weapon yield increases. Instead of being disappointed at the spread of values and lack of correlation of V/U with M , one may conclude that these numbers are remarkably constant in view of the differences in Mach number, the differences in the mechanisms of cratering, and the variability of the properties of the soils.

To summarize the size effects:

(a) Impact—No size effects for aluminum with particle sizes from $\frac{1}{8}$ " to $\frac{1}{2}$ " at Mach numbers from 0.06 to 0.6; nor for lead and magnesium-lithium with 0.22 and 0.50" cylinders at $0.25 < M < 1.5$ and $0.60 < M < 1.7$, respectively; nor for concrete with projectile weights from 1.7 to 1000 lbs. at $M \cong 0.1$.

(b) Explosions—No size effects for small charges in soil, but the volume-energy ratio decreases as size increases for very large charges.

Summarizing Mach number effects:

(a) Impact—Wax, lead, magnesium, magnesium-lithium, and brass with sparse data up to $M \cong 5$ showed no correlation of the volume-energy ratio with Mach number. Aluminum, tested more thoroughly in the subsonic range, showed a distinct increase in V/U up to $M \cong 0.6$ and a tendency to become constant at higher Mach numbers.

(b) Explosions—Explosions in soil at very high Mach numbers showed results comparable with the results of impact at $M \cong 0.5$, although many undetermined effects were included in the data.

If emphasis is placed upon the scarcity of experimental data and the fact that the test results at a single condition may show a spread of values of 3 or 4 (which tends to obscure any correlations), it becomes apparent that any conclusions drawn from these test results must of necessity be preliminary in nature. Pending further systematic experimentation into the effects of projectile velocity, shape, composition, and size the estimate is made that the volume-energy ratio is a constant of the target material. Use of this ratio (not securely established even within the range of values of the parameters considered) for estimates at 10 times the test velocity and with particles 100 times as small as the test pellets appears to be a questionable procedure. However, since there is no obvious reason why the ratio should change beyond the conditions tested, and since the linear dimensions of the crater

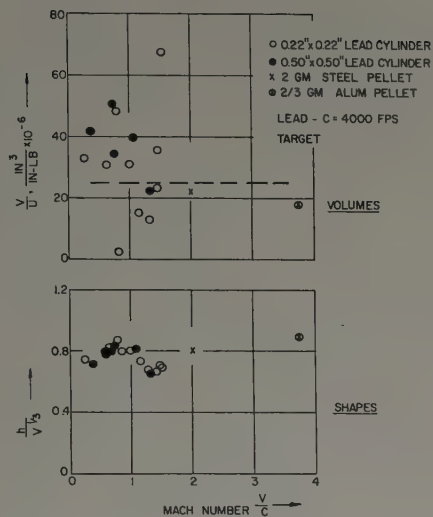


FIG. 2. Experimental Data—Lead Source: Ref. 3, 5

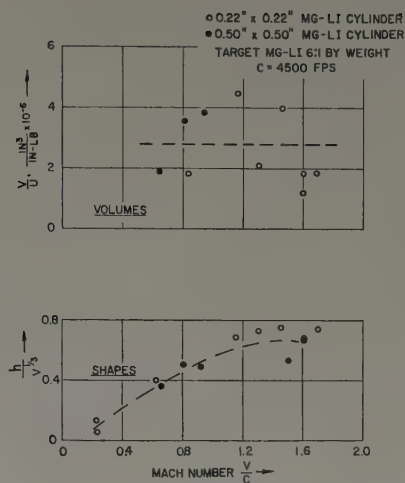


FIG. 5. Experimental Data—Magnesium-Lithium Source: Ref. 5

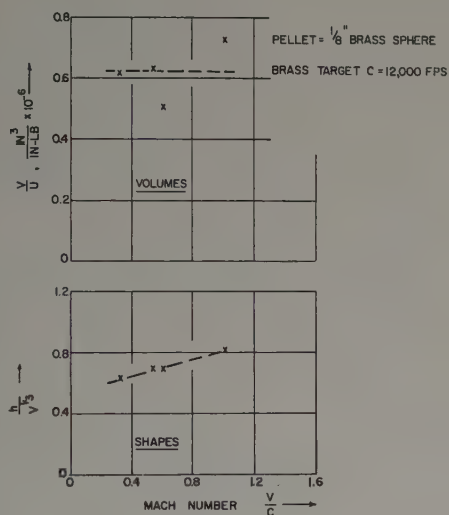


FIG. 3. Experimental Data—Brass Source: Ref. 4

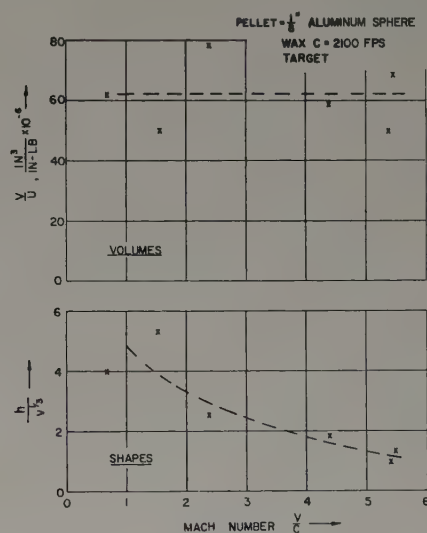


FIG. 6. Experimental Data—Wax at 50°F Source: Ref. 4

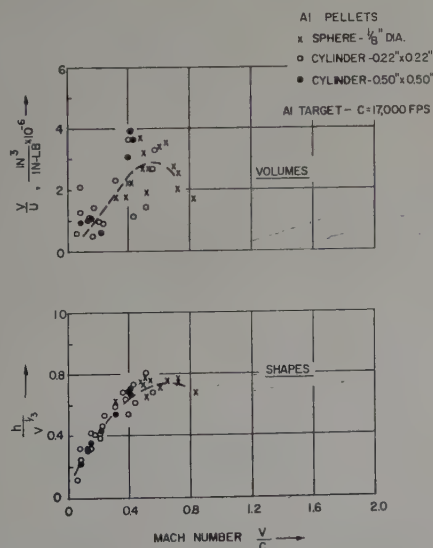


FIG. 4. Experimental Data—Aluminum Source: Ref. 5, 8

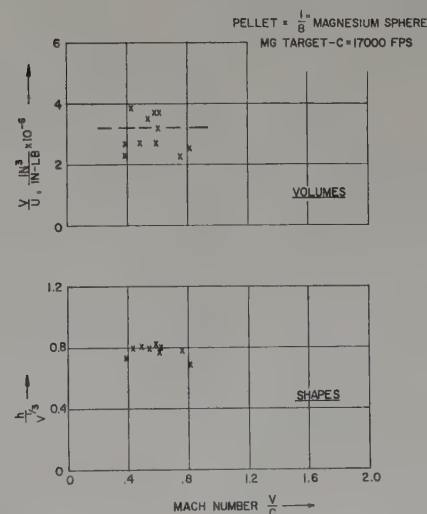


FIG. 7. Experimental Data—Magnesium Source: Ref. 4

vary only as the $\frac{1}{3}$ power of the volume, it is recommended that the constant volume-energy ratio be used for estimates of penetration at high velocities.

Several physical properties of the target material have been proposed as the parameter for correlation with the volume-energy ratio; namely, modulus of elasticity, speed of sound, and heat of fusion (Ref. 4). The best correlation appears to be with modulus of elasticity, the reciprocal of which has the same dimensions as the volume-energy ratio. Fig. 8, which consists of a plot of the product of the volume-energy ratio and the modulus of elasticity versus modulus of elasticity (also see Table II), indicates that the correlation is rough. Use of the curve drawn through the scattered points (V , U and E in consistent units)

$$\frac{VE}{U} = 17.5 \left[\frac{E}{E_0} \right]^{0.26} \quad (1)$$

for prediction of crater volumes for untested target material appears to fit the test points within about 1 order of magnitude.

Note that Fig. 8 represents a composite picture of the experimental data, obtained by lumping all data together regardless of Mach number, pellet size, pellet material, and other possibly significant parameters. It is anticipated that the scatter will be reduced when the effects of all important parameters are evaluated and taken into account. For example, one should perhaps consider concrete and plaster-of-paris as brittle materials and thus to be classified separately from the ductile materials—thereby reducing the spread of data. Unfortunately, it is much too early to attempt such refinements, and Eq. (1) is proposed as the best rule-of-thumb estimate available at present.

The Shapes of Craters

Correlation of data on crater shapes is far more satisfactory than the correlation of the volume data, if one considers only the data obtained at high enough speeds to produce bowl-shaped or conical craters (at low velocities the projectile produces a hole in a ductile target with a diameter about equal to its own diameter). Without regard to the reasons for variation in shape such as materials or Mach number or size the total variation in shallowness (either h/D or $h/V^{1/3}$) is within one order of magnitude, while the volume data had such a spread even after correlation.

Figure 9, taken from Baldwin's excellent book "The Face of the Moon" (Ref. 9) represents an attempt to assess the "size effect" on crater shape independently of the effects of Mach number or materials. For the meteorite craters on earth and the moon (depths of crater from 10 feet to about 10,000 feet) this correlation may be fairly valid, since one would expect the meteorites to travel at speeds which are not dependent upon size. However, it must be noted that the portion of the curve from 1 foot to about 100 feet in depth was obtained at very much lower Mach numbers than the

meteorite data, and it may well be the effect of Mach number which is pictured in this part of the curve. For this reason, the conclusion is reached that the larger the crater, the smaller the value of $h/V^{1/3}$ for 10 feet $h < 10,000$ feet, with no statement with regard to craters smaller than 10 feet in depth. This conclusion is substantiated by our experience in explosive cratering, where the small craters scale reasonably well but the very large craters become shallower in shape.

Information on the size effect on crater shape for materials other than earth indicates that the effect is negligible, at least for the range of values tested. This range includes impact on concrete at a single velocity using projectiles from 1.7 lbs. to 1000 lbs., as well as impact on several metals using pellets $\frac{1}{8}$ " to $\frac{1}{2}$ " in diameter at many Mach numbers. It is concluded, there-

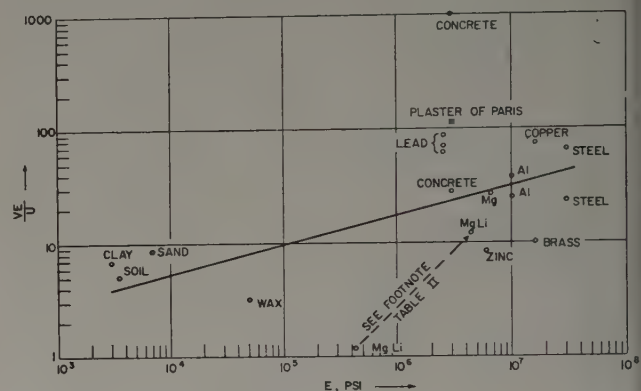


FIG. 8. Crater Volumes—Correlation

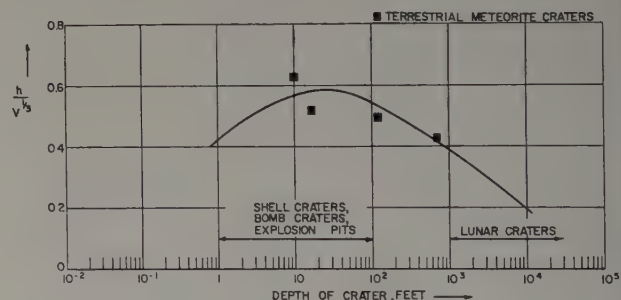


FIG. 9. Effects of Size on Shapes of Craters in Soil Source; Ref. 9.

fore, that the crater shape is independent of size, except for crater depths above about 10 feet and perhaps for very small particle sizes.

Figure 10 illustrates the correlation of crater shallowness with Mach number, regardless of materials or sizes. Note that an effective "impact speed" of about 5000 fps was assumed for the high explosive cratering, and the meteorite impact Mach number was simply placed at the edge of the plot (the velocity range 11 to 73 km/sec would correspond roughly to Mach numbers from 70 to 400). Thus we find an approximate method of making use of the only source of experimental data obtained at very high Mach numbers, at least insofar as the effect upon shape of crater.

The most radical aspect of such extrapolation to very high Mach numbers is, in the opinion of the author, the fact that it is based upon only one material—soil. The only other data on crater shapes at high Mach number is for wax (Ref. 4), and this information consists of 5 holes of elongated shape and only one bowl-shaped crater at $M \cong 5.5$ (see Fig. 5). Values of $h/V^{1/3}$ for wax drop rapidly from about 5 at $M = 1$ to about 1 at $M = 6$. Whether the wax curve would fair into the extrapolated curve of Figure 10 is problematical. It is therefore highly desirable to have some idea of the mode of cratering of a specific material before attempting to make use of the single curve of Figure 10. Without the benefit of information on the manner of cratering, however, a fairly conservative number for crater shallowness appears to be the peak of the curve, namely

$$\frac{h}{V^{1/3}} = 0.8 \quad (2)$$

for supersonic Mach numbers.

The Depths of Craters

In order to estimate the depth of penetration below the original surface of the target, one may combine

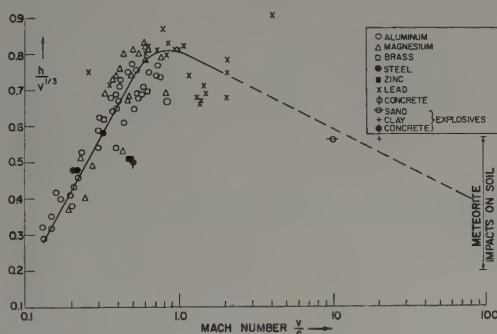


FIG. 10. Effect of Mach Number on Shape of Crater (see Fig. 1 for ideal crater shapes).

Eq. (1) and Eq. (2), with consistent units for U , E , and h :

$$h = 2 \left[\frac{U}{E} \right]^{1/3} \left[\frac{E}{E_0} \right]^{0.09} \quad (3)$$

It is estimated that Eq. (3) will prove accurate within a factor of about 2 or 3 for materials which characteristically produce bowl-shaped or conical craters, and

quite inaccurate for soft materials such as wood which permit deep penetration with a small hole diameter. Note that oblique impacts generally result in lower values of h and V , although for brittle materials the volume may increase somewhat with obliquity (Ref. 4 and 10).

The present paper correlates the experimental data on high-speed cratering using existing data which are somewhat incomplete. The resulting equations should prove useful however, in providing order-of-magnitude estimates of crater depths and volumes which may be applied to the calculation of penetration or surface roughness caused by meteoroid impacts. Although it is not anticipated that future investigation will radically change the conclusions reached herein, there are many areas of assumption which demand further scrutiny. In particular, experimental programs are recommended to isolate the effects of Mach number, size, and physical properties of the pellet; to classify materials into types such as soft, brittle, ductile, etc; and to approach the actual environmental condition of about 70 km/sec.

Bibliography

1. WHIPPLE, F. L. "Meteoritic phenomena and meteorites" Physics and Medicine of the Upper Atmosphere, U. of New Mexico Press 1952
2. HELIÉ, F. "Portions of Traite de Balistique Experimentale which deal with terminal ballistics", Chap. III, IV, V and XIV Paris (1884) Translated by J. S. Rinehart—NOTS Tech. Memo RRB-75, 1 May 1950
3. RINEHART, J. S., AND PEARSON, J. "Behavior of metals under impulsive loads" ASM, Cleveland, Ohio 1954
4. VAN VALKENBURG, M. E., CLAY, W. G., HUTH, J. H. "Impact phenomena at high speeds" J. Ap. Phys. vol. 27 no. 10 October 1956
5. HUGH, J. H., THOMPSON, J. S., AND VAN VALKENBURG, M. E., "Some new data on high speed impact phenomena" J. App. Mech. vol. 24, no. 1 pp. 65-68 March 1957.
6. "Effects of Impact and Explosion" Div. 2, NDRC, Vol. 1, OSRD 1946
7. RINEHART, J. S. "Some observations on high-speed impact" NOTS Tech. Memo RRB-50 1 November 1950
8. COLE, R. H. "Underwater Explosions" Princeton Univ. Press 1948
9. BALDWIN, R. B. "The Face of the Moon", U. of Chicago Press 1949
10. RINEHART, J. S., WHITE, W. C. "Shapes of craters formed in plaster of paris by ultra-speed pellets" Am. J. Phys. vol. 20 no. 1, Jan. 1952
11. TAYLOR, D. W., WHITMAN, R. V. "The behavior of soils under dynamic loadings—2. Interim report on wave propagation and strain-rate effect" MIT, AFSWP-117, July 1953

Temperature Equilibria in Space Vehicles*

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Abstract

The equilibrium temperature reached within a space vehicle moving within the solar system is discussed. The effects of vehicle configuration, vehicle attitude, surface properties, and internal heat release are evaluated. Particular attention is given to methods of vehicle design whereby the range of equilibrium temperatures can be set at some desired value.

Introduction

Several factors which determine the temperature environment within a space vehicle will be discussed in this paper. It has been assumed throughout that the vehicle is operating within the solar system

be assumed to be at uniform temperature. Such a space vehicle is shown schematically in Figure 1. The quantity, Q_s , denotes the heat which flows into the vehicle through its external surface from solar radiation. A much smaller amount of radiation is also received from the planets and from the other stars.

Eddington¹⁰ has estimated that a passive black body in interstellar space will reach an equilibrium temperature of 3.18°K. The corresponding radiation flux is 5.68×10^{-3} ergs $\text{cm}^{-2} \text{sec}^{-1}$. More recently, a compatible estimate has been made by Ambartsumyan.¹¹

The total energy brought to earth by cosmic rays has been stated by Neher¹² to be about equal to that of starlight. Even if the incident energy flux due to cosmic rays and other unknown factors is 10^4 times larger than previously estimated,¹³ the equilibrium temperature of an inert black body in interstellar space will still be less than 40°K; the corresponding effect on the equilibrium temperature of a space vehicle within the solar system will be trivial. The vehicle may also have an internal heat source, such as a nuclear or chemical power supply. The rate at which the heat is released internally is denoted by Q . The vehicle will itself radiate energy into space at a rate Q_r . From the first law of thermodynamics and the requirement that steady state conditions prevail, it follows that

$$Q_s + Q = Q_r \quad (1)$$

At a distance from the sun equal to that of the earth, the total energy contained in the electromagnetic radiation striking the vehicle's surface is about 1.35 kilowatts/meter²† or about 125 watts/foot². Most of this energy is in the visible portion of the spectrum. The intensity of this solar flux in other portions of the solar system is given in Table 1.

It is to be noted that on the surface of Mercury, the intensity of solar radiation is almost seven times what it is on Earth, while on Pluto, it is less than $1/1500$ as strong as on Earth.

Equilibrium Temperatures

Only part of the solar radiation striking the surface of the vehicle is absorbed. The portion not absorbed is reflected. The term "absorption coefficient" is usually used to denote the fraction of incident light at some particular wave length which is absorbed by a surface. Experimentally, the absorption coefficient is

† Based on a solar constant of 1.94 cal $\text{cm}^{-2} \text{min}^{-1}$ as measured outside the earth's atmosphere.⁸ More recently, a value of 2.00 ± 0.4 cal $\text{cm}^{-2} \text{min}^{-1}$ has been proposed.⁹

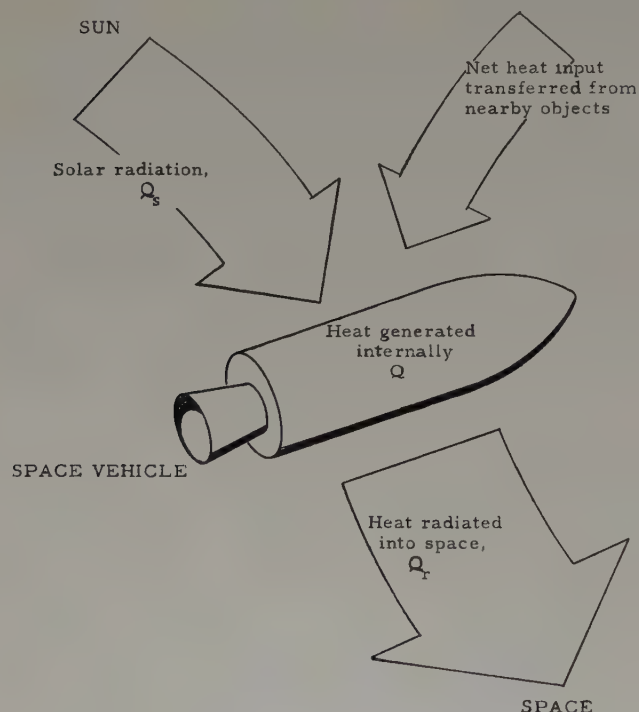


FIG. 1. Heat balance within a space vehicle

some distance from any planet. It is further assumed that steady state conditions have been reached.

Papers dealing with related subject matter have been written by several authors.¹⁻⁷

Heat Exchange

During the first part of the discussion attention will be directed to cases in which the thermal conductivity of the vehicle is so large that the body may

* Presented at the Western Regional Meeting, August 18-19, 1958, Palo Alto, Calif.

observed to be a function of the wave length of the incident light, the direction at which the light impinges on the surface, and, to a smaller extent, the temperature of the material. The term "absorptivity," A , is here used to denote the absorbed portion of the total incident solar radiation striking the vehicle surface and the term "albedo" to represent the reflected portion.

Radiation from the surface of the vehicle is at the rate,

$$Q_r = \sigma ET^4 \text{ kw/ft}^2. \tag{2}$$

Here σ is the Stephan Boltzman constant, E is the emissivity of the surface material, and T is its absolute temperature. The optical properties of some common materials are given in Table 2.

With Equation (1), Equation (2), and optical properties data of the external surface of the vehicle, the equilibrium temperature of the assumed space vehicle can now be computed. The method used here is identical to that used by Sternberg¹ and others. The surface

TABLE 1
Intensity of solar radiation

Distance from Sun, Astronomical Units	Total Radiation Flux	
	watts/ft ²	kw/m ²
0.01 —	1.25×10^6	1.34×10^4
0.1 —	1.25×10^4	1.34×10^2
0.387 (Mercury)	835.	8.95
0.723 (Venus)	238.6	2.55
1.0 (Earth)	125.	1.34
1.52 (Mars)	54.1	0.580
5.20 (Jupiter)	4.62	0.0496
9.54 (Saturn)	1.37	0.0147
10.19 (Uranus)	0.339	0.364×10^{-2}
20.1 (Neptune)	0.139	0.149×10^{-2}
39.5 (Pluto)	0.080	0.859×10^{-3}
100.0 —	0.0125	1.34×10^{-4}

TABLE 2
Optical properties of various materials*

Material	°F	Absorption Number A	Emissivity E	E Ratio A/E
Silver	100	0.04	0.02	2.0
Aluminum, polished	100	0.10	0.05	2.0
	1000	—	0.06	—
Aluminum, 2024, buffed and polished ⁹	100	0.34-0.37	0.03	12.0
Stainless steel, black	100	—	0.90	—
	1000	—	0.90	—
Stainless steel, polished	100	0.40	0.05	8.0
Fused quartz, bricks	100	0.1-0.4	0.90	0.2
Hard rubber, asbestos	1000	—	0.90	—
Lamp black	100	0.95	0.95	1.0
	1000	—	0.95	—
SiO on polished metal ⁷	100	0.1	0.90	0.1
MgO ⁹	100	0.15	0.97	0.15
Titanium, 6Al-4V ⁹	100	0.8	0.18	4.4

* Buettner² states that the ratio of absorptivity of solar radiation to the low temperature emissivity may vary "from ten for ideally polished metals such as aluminum and nickel, to one-tenth for ideal white."

temperature is uniquely fixed by the requirement that the temperature must be high enough to radiate into space all heat generated within the vehicle or absorbed by its surface (Equation 1). Sample calculations are shown in Figures 2, 3 and 4. In these cases it is assumed that no heat is released within the vehicle. In other words, the vehicle is moving passively through space.

Figure 2 should not be used to compute the equilibrium temperature of low altitude terrestrial satellites. Such a satellite is usually shielded from solar

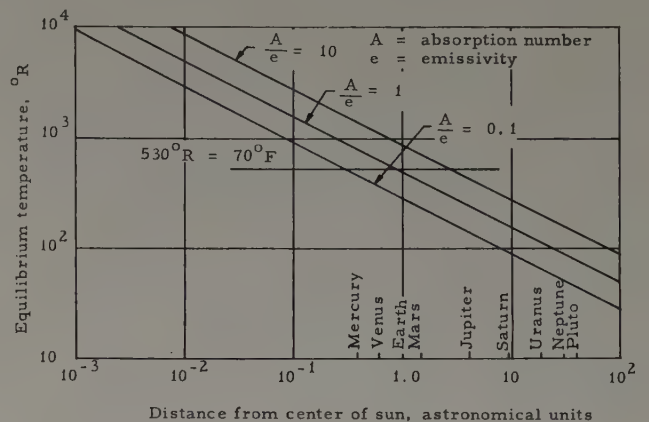


FIG. 2. Equilibrium temperature of an inert sphere

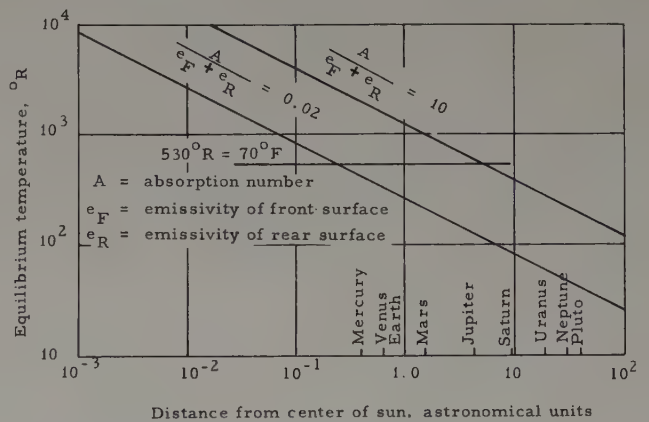


FIG. 3. Equilibrium temperature of a thin plate normal to the sun.

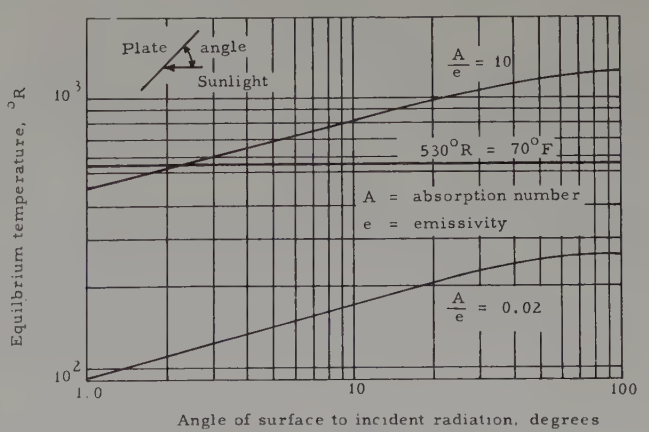


FIG. 4. Effect of attitude on equilibrium temperature of a thin plate located at one astronomical unit from the sun.

radiation during an appreciable portion of its period. Likewise, such satellites are exposed to reflected solar radiation as well as radiation from Earth. The methods used to compute temperature of a sphere under these conditions has been discussed by Tousey⁷ and others.^{2, 4}

The effect of an internal heat source on the equilibrium temperature of a body in space can be determined from Figure 5. The same figure can be used for any portion of the vehicle if the portion in question is thermally insulated from other portions of the vehicle, is exposed, and is radiating.

Control of Temperature Environment

If the attitude of the vehicle can be controlled, a powerful new tool is placed in the hands of the designer responsible for specifying the temperature environment. The same aspect of the vehicle can be presented to the sun at all times. If low vehicle temperatures are desired, the portions of the vehicle surface exposed to the sun can be made highly reflective, while the unexposed portions can be covered with some material having good radiative properties. Alternatively, by changing the shape of the vehicle, the area exposed to sunlight can be made quite small in comparison with the portions unexposed or shaded. In many cases, however, it will be found to be more practicable to provide a power driven refrigeration machine to cool portions of a space vehicle than to install the extensive special radiating surfaces suggested above.

Conversely, if it is desired to maintain a high equilibrium temperature in the vehicle, a large parabolic reflector can be arranged so as to reflect solar radiation on the important elements of the vehicle, which are then placed at the focal point of the mirror and surface coated with material having a high absorbtivity.

Vehicle Structure

The restriction that all portions of the vehicle surface be at the same equilibrium temperature is not always desirable. For example, the parabolic reflector just described will not, in general, be at the same temperature as the bodies located at its focus. In general, the heat received by a vehicle from solar radiation will be reduced if the illuminated portions of the surface are insulated thermally from the rest of the vehicle structure. One way to reduce solar heat input is to use an umbrella or radiation shield arranged so as to shadow the vehicle. Two possible arrangements are shown in Figure 6.

In Figure 6A, the shield is placed so close to the vehicle surface that only the front sunlit side is free to radiate into space. In Figure 6B, the radiation shield is placed far enough in front of the rest of the vehicle so that both sides of the shield can radiate into space effectively.

Radiation shields and thermal insulation are also desirable in many vehicles in which electric propulsion is used. In such vehicles, appreciable amounts of ther-

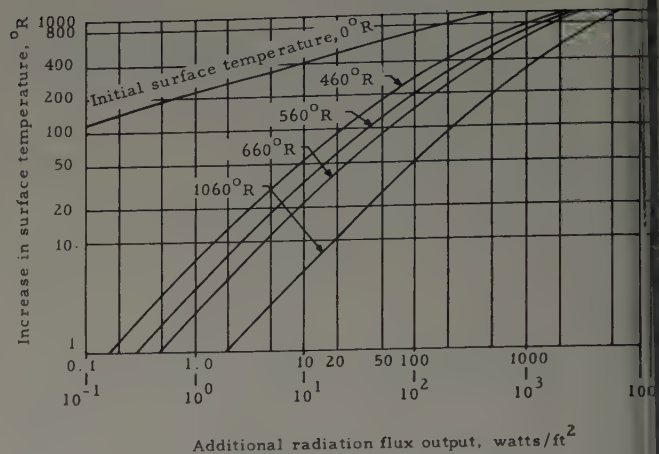


FIG. 5. Effect of added heat input on equilibrium temperature.

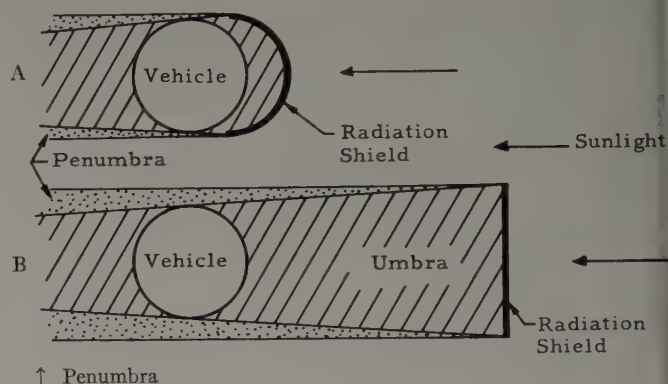


FIG. 6. Two types of radiation shielding

mal energy must be radiated from the propulsion section of the vehicle. Often the temperature of the radiator will be high. Radiation emitted by a high temperature radiator and impinging on other exposed portions of the vehicle might result in excessive temperatures. Thus, radiation shielding and thermal insulation might both be needed to maintain an acceptable temperature in the cargo or payload portion of such vehicles.

Rather involved designs may be required by some types of actual space vehicles. A design which may provide a satisfactory temperature environment within the vehicle when located in one part of the solar system may be completely inadequate at some later time when the vehicle is located at a different distance from the sun. To a certain extent, compensation for these changes in the intensity of incident flux of solar radiation may be obtained by appropriate changes in the attitude of the vehicle, or by changing the optical properties of its external surfaces. However, in most applications, rather more drastic changes are required in order to cope with a factor of 10^4 in radiation intensity, as in traveling from Mercury to Pluto, for example.

Some interesting problems are associated with the temperature control problems of vehicles designed to approach close to the sun. As shown on Figure 3, a flat plate with suitable optical properties i.e. with $A/(e_F + e_R) = 0.02$, can be placed at 0.018 astronomical

units (less than twice the sun's diameter) from the center of the sun without exceeding a temperature of 2000°R . Such a flat plate can, in turn, be used to shield a vehicle, as shown in Figure 6B. Under these conditions, the angle subtended by the shield at the vehicle must be almost 30° , in order to shut out the sun's disc. A spherical vehicle placed at a distance slightly less than twice the shield diameter behind such a shield would have $1/58$ of its total solid angle, i.e., $1/58$ of 4π steradians, obstructed by the shield. If placed at a greater distance the vehicle would no longer lie within the umbra. If the surface emissivity of the sphere were equal to the absorption number, the equilibrium temperature will be $2000^{\circ}\text{R} \times 1/(58)^{1/4} = 724^{\circ}\text{R}$,—still too high for comfort. However, the same conceptual approach can be used if a second radiation shield, rather than a sphere, is placed behind the first shield. If this second shield is, in turn, used as a shield for a spherical vehicle placed at a distance behind the second (and smaller) shield, a second factor of temperature reduction will be obtained, and thus acceptable cabin temperatures can be achieved.

The same principle of cascading a number, n , of radiation shields can be used with the arrangement shown in Figure 6A.

The temperature of the first (nearest the sun) shield, T_1 , can be obtained from Figure 3, setting the emissivity of the rear surface, e_R , equal to zero, since the heat radiated back through the cascade of shields is small compared to the heat radiated from the front surface. If the emissivity, α , of the shield surface is small compared to one, and R is the ratio of shielded area to exposed area, radiation-wise, of the vehicle (about 0.5 for a spherical vehicle), and the emissivity of the exposed area of the vehicle is ϵ , it can be shown¹⁴ that the vehicle temperature, T_2 , will be given by

$$T_2 = \left(\frac{R\alpha}{2\epsilon n} \right)^{1/4} T_1 \quad (3)$$

An inert spherical vessel, having an emissivity, ϵ , of one, and located as before, at 0.018 astronomical units

from the center of the sun, and placed behind 10 (i.e. $n = 10$) closely spaced shields, each (except for the exposed outer surface of the first shield) having an emissivity, α , of 0.04, will have an equilibrium temperature, T_2 , of about 400°R . However, due to the change in the radiative properties of its rear surface, e_R , the temperature of the first shield (nearest the sun) will be increased by a factor of $2^{1/4}$, in other words, from 2000°R to 2400°R .

References

1. STERNBERG, R. L., Some Remarks on the Temperature Problems of the Interplanetary Rocket, *Journal of the American Rocket Society*, **70**: 34-35, 1947.
2. BUETTNER, KONRAD, Thermal Aspects of Travel in the Aeropause, in C. S. White and O. O. Benson, *Physics and Medicine of the Upper Atmosphere*, p. 89, Univ. of New Mexico Press, 1952.
3. SANDORFF, P. E. AND JOHN S. PRIGGE, JR., Thermal Control in a Space Vehicle, *Journal of Astronautics*, **3**: 4-8, 26, 1956.
4. SCHMIDT, CRAIG M. AND A. J. HANAWALT, American Rocket Society Meeting, 26 November, 1956.
5. JOHNSON, F. S. ET AL., The Ultraviolet Spectrum of the Sun in R. L. F. BOYD AND M. J. SEATON, *Rocket Exploration of the Upper Atmosphere*, Interscience, 1954.
6. NAUGLE, JOHN E., The Temperature Equilibrium of a Space Vehicle in ALPERIN, MORTON, ET AL., *Vistas in Astronautics*, pp. 157-158, Pergamon Press, 1958.
7. TOUSEY, R., Optical Problems of the Satellite, *Journal of the Optical Society of America*, **47**: 261, 1957.
8. Smithsonian Institute, Smithsonian Meteorological Tables, Table 130, 1951, Sixth Revised Edition.
9. LEWIN, JOSEPH S., Thin Pressurized Shells Look Best for Space Structure, *Aviation Age*, **29**: 178-179, 181-185, 1958.
10. EDDINGTON, A. S., *The Internal Constitution of the Stars*, Cambridge Univ. Press, p. 371, 1926.
11. AMBARTSUMYAN, V. A., editor, *Theoretical Astrophysics*, Pergamon Press, p. 582, 1958.
12. NEHER, M. V., Cosmic Rays in Space in ALPERIN, MORTON, ET AL., *Vistas in Astronautics*, pp. 159-161, Pergamon Press, 1958.
13. VAN ALLEN, JAMES, ET AL., Radiation Measurements from Explorer IV, Research Report SUI 58-8, Dept. of Physics, State University of Iowa.
14. BOELTER, L. M. K., ET AL., *Heat Transfer*, p. xviii-10, University of California Press, 1942, (mimeographed).

Book Reviews

The Exploration of the Moon, Arthur C. Clarke, Harper & Bros., New York, 1954, \$2.50 (112 pgs).

This is an introductory text aimed primarily at giving a visual presentation of steps toward the conquest of space. Beginning with the launching of the first atomic missile, it covers such things as refueling in space, landing on the moon, establishing a lunar colony; and with the moon as a future base of operations, the ultimate mastery of more remote worlds and planets. Realizing how a picture is worth a thousand words, Mr. Clarke enlisted the aid of R. A. Smith to illustrate profusely through the text via drawings of possible configurations based on known technical advancements in the field. Each illustration has an explanatory facing page. Means of flight, logistical support, construction, and use of local materials for housing a planetary colony are dramatically portrayed.

The book is divided into four phases; namely:

1. The establishment of the first orbital satellite circling the earth, just beyond the limits of the atmosphere.
2. The circling of the moon by a robot vehicle and the depositing on the moon of man-made instruments.
3. The first lunar landing and establishment of human settlements or colonies. Coupled with this is a description of possible utilization of indigenous materials to construct and operate these colonies.
4. The establishment of a permanent moon base and its use as a point of departure for travel to other planets. The only deterrent immediately present, according to the author,

concerning planetary flight is the harnessing of nuclear energy which now appears likely in the not too distant future.

Basically, this text is for the layman interested in the new science of astronautics. Technically accurate, the material is presented for the non-technical reader who is interested in a general survey of the field.

O. FRANK KATTWINKEL

The Handbook Of Rockets And Guided Missiles by Norman J. Bowman. Perastadion Press, Chicago, 1957, \$6.50.

This book contains a collection of much of the available published missile and rocket characteristics and performance. These data were obtained mainly from aviation periodicals and the press. While this source of information may not always be accurate and complete, the compilation will no doubt prove useful to many technical writers and certain technical personnel. Because of the rapid developments that are now taking place in the missile and rocket fields, this volume is limited as an important reference work for weapon systems designers. Frequent addition to and revision of the data that are presented would be necessary on a continuing basis in order to provide a handbook of lasting significance.

Noteworthy in the compilation of data is the inclusion of armament and missiles developed by foreign nations. The collection and organization of data in this connection is a worthwhile contribution of this Handbook.

H. L. SHAPIRO

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At the suggestion of various members of the Society the Technical Papers Committee Chairman, *Dr. Horace Jacobs*, has prepared a sample sheet of the basic requirements for technical papers to be submitted for possible inclusion in various AAS meetings. This is reproduced at this time for wide distribution. Abstracts of such communications should be typed single-spaced in a text width of 4.5 inches centered below the title and author(s) of the paper. The abstract can be brief and should not exceed 300 words in length.

1. *Introduction.* A technical paper for publication in the AAS Proceedings should be typed on a good quality bond, 8½ x 11 inches. Except for the abstract, page width is 6½ inches and page length is 9 inches. Copy should be typed in standard elite, preferably on an electric typewriter, and should be suitable for offset. Corrections should be stripped in rather than erased. Text is single-space with double-space between headings, equations, items, and paragraphs. Major heads are all caps and flush left.
2. *Other Main Headings.* The paper can be divided into principal sections as appropriate. Headings or paragraphs are not numbered. Secondary headings are in caps and lower case; they are flush left and underlined.

a. *Equations.* Equations are as follows:

$$(a^2m_0/at^2)(a^2m_0/as^2) = 0 \quad (1)$$

Slashes should be used to separate numerator and denominator if it is conveniently possible. Equations are referenced in the text as equation (1), (2), etc.

b. *Symbols.* Slashes are also preferred to separate numerator and denominator in the text: $m_i = m_0 \exp(-v_i/c)$. Where superscripts and subscripts make single-space typing impractical, the lines where they occur can be typed in space-and-a-half or in double-space.

c. *Greek Symbols.* If tertiary headings are necessary they are flush left, upper and lower case, and underlined; text is run-in. Greek symbols can be prepared in one of the following ways:

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- (2) Typed by a mathematical typewriter
- (3) Hand-drawn. If this method is used the following should be noted: Use black or red ink, Draw symbols neatly.

Above is an example of format for enumerations. They are indented 5 spaces.

- d. *Tables.* Table headings are centered above the table and have the following format:

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- e. *Figures.* Line drawings suitable for reproduction may be inserted by the author at appropriate places in the text. If this is done, figures should be reduced consistent with clarity and space conservation. Captions are centered below the figure and have the following format:

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If line drawings are not inserted in the text they should be provided as original artwork or photostats suitable for reproduction. Glossy black and white prints should be provided for half-tone photographs. Each figure should be numbered and a caption provided.

- f. *References and Footnotes.* References listed at the end of the paper are indicated in the text by a superscript Arabic number¹. Footnotes are called out in the text by superscript symbols *, **, †, ‡, etc. Standard practices footnotes and references are acceptable.

3. *Conclusion.* The AAS would appreciate it if each author would provide the Society with at least 100 preprints of his technical paper before the beginning of the session. These preprints should be presented in the format indicated above. However, illustrations might be interspersed in the text or placed at the end of the paper.

4. References.

1. C. S. Draper, Education in the Astronautical Sciences, *J. Astronautics*, Vol. IV, No. 2, pp. 29-30, 1957

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- 57-7 OPTIMUM BURNING PROGRAM AS RELATED TO AERODYNAMIC HEATING FOR A MISSILE TRAVERSING THE EARTH'S ATMOSPHERE, by Angelo Miele, Purdue University, Lafayette, Ind.

- 57-23 AN UNIVERSAL RADIO ASTRONOMY SYSTEM FOR RADIO TELESCOPES, SPACE VEHICLE TRACKING AND SCATTER PROPAGATION STUDIES, by George J. Doudoulakis, Electronics Div., General Bronze Corp., Garden City, N. Y.
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